Part 5

Pulsars and Other Neutron Stars

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Pulsars: A Roundup of Recent Results

R. N. Manchester
Australia Telescope National Facility, CSIRO, Epping NSW 1710, Australia

Abstract. The past few years have been a very exciting time in the field of pulsar astronomy. A major factor in this has been the advent of the large X-ray observatories but innovations in radio astronomy have also made a significant contribution. In this article I review some of the more interesting results, especially those relating to searches and pulsar – supernova remnant associations.

1. Introduction

Pulsar astronomy is currently undergoing something of a renaissance. In the last few years, the number of known pulsars has more than doubled to more than 1500, largely as a result of searches using a multibeam receiver on the Parkes radio telescope. Many detailed and indeed beautiful images of supernova remnants (SNRs) have been produced, principally using *Chandra* observations and a significant number of these show interactions between a central pulsar and the surrounding medium. Another area which has seen significant advances in the past few years is the detection and study of millisecond pulsars in globular clusters. Finally, with improved data recording and analysis techniques, many interesting results have been obtained from studies of previously known pulsars.

2. Pulsar Surveys with the Parkes Multibeam System

The Parkes multibeam receiver was installed on the Parkes 64-m telescope in mid-1997. It has 13 beams arranged in two hexagons surrounding a central beam, each with dual polarization (Staveley-Smith et al. 1996). Pulsar searches use a filterbank receiver/digitiser system with 96×3 MHz channels, centered at 1374 MHz, on each polarization of each beam. Several searches have been made with this system and I describe two of them here: the Parkes multibeam pulsar survey and the Swinburne intermediate-latitude survey.

The Parkes multibeam pulsar survey is a collaboration between groups from the United Kingdom, United States, Italy, Canada and Australia and covers a 10°-wide strip along the southern Galactic plane between Galactic longitudes of 260° and 50°. It commenced in August, 1997, and has been outstandingly successful, discovering more than 620 pulsars. The receiver, data recording and analysis systems, and the discovery of the first 100 pulsars, were described in detail by Manchester et al. (2001). The survey has a limiting flux density of approximately 0.2 mJy, several times more sensitive than any previous

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large-scale survey, and uses a sampling interval of 250 μs. It achieves this high sensitivity with a combination of low system noise ($\sim$ 22 K), wide bandwidth (288 MHz) and long integration time (35 min). Following determination of accurate periods and positions, newly discovered pulsars are listed on a website (http://www.atnf.csiro.au/research/pulsar/pmsurv/). This site currently lists parameters for 519 pulsars.

Because of the high sensitivity of the survey, most of the newly discovered pulsars are relatively distant and have high dispersion measures (DMs). The median DM for multibeam pulsars is ~ 350 cm^{-3} pc compared to ~ 90 cm^{-3} pc for previously known pulsars. Current models for the Galactic electron density distribution (e.g., Taylor & Cordes 1993) place many of the pulsars at distances comparable to the Galactic Center and even beyond. They therefore form an excellent sample for studies of the interstellar medium, including improvement of the electron density model and investigations of the interstellar magnetic field (e.g., Han et al. 2002).

A complementary survey, optimised for detection of millisecond pulsars, is being undertaken by a group from Swinburne University of Technology and Caltech using the multibeam receiver at Parkes. This survey is covering several strips parallel to that of the Parkes multibeam survey but at higher latitudes. It uses a smaller sampling interval, 125 μs, and just 4 min per pointing. While this survey has a lower sensitivity overall, these parameters give it a relatively higher sensitivity to millisecond pulsars. The first phase of the survey (Edwards et al. 2001) covers strips with $5^\circ < |b| < 15^\circ$ and has been very successful, discovering 69 pulsars including eight millisecond pulsars.

One of the basic pulsar parameters is the slow-down rate, normally expressed as a dimensionless period time-derivative $\dot{P}$. Measurement of this parameter allows determination of the characteristic age of the pulsar, $\tau = P/(2\dot{P})$, and the surface-dipole magnetic field, $B_s = 3.2 \times 10^{-19} P\dot{P}$ G. The P–$\dot{P}$ diagram, shown in Fig. 1 for all known pulsars, is a basic tool of pulsar astronomy. Young pulsars have high surface-dipole fields and spin down rapidly, whereas millisecond pulsars have very small period derivatives, implying low magnetic fields and ages of 10^9 years or more. A large proportion of millisecond pulsars are binary. Also shown in Fig. 1 are the so-called 'anomalous X-ray pulsars' (AXPs) and 'soft gamma-ray repeaters' (SGRs) which have long pulsation periods and extremely strong implied magnetic field strengths. AXPs and SGRs are detected only at X-ray and higher energies. Some young pulsars, including the fastest known, PSR J0537-6910 in the Large Magellanic Cloud (Marshall et al. 1998), are also detectable only at X-ray or γ-ray energies.

One of the more significant results to come from the Parkes multibeam survey is the detection of a large number of relatively young pulsars with very large implied magnetic-field strengths. Indeed, as Fig. 1 shows, the ten radio pulsars with the largest derived magnetic field strengths were all detected in this survey. Some of these pulsars have relatively long periods and are located close to the region of P–$\dot{P}$ space occupied by the AXPs and SGRs (Camilo et al. 2000a). Despite this, these are radio pulsars, so far undetectable at X-ray wavelengths (Pivovaroff et al. 2000). AXPs and SGRs, on the other hand, have no detectable pulsed radio emission.

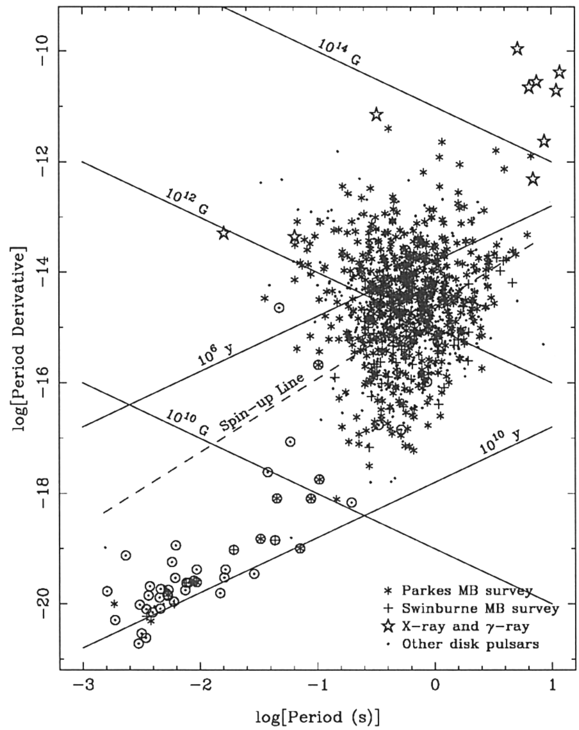

Figure 1. Distribution of known Galactic disk pulsars in the P–$\dot{P}$ plane. Binary pulsars are indicated by circle around the point and pulsars detected only at high energies are marked with an open star. This latter group includes the anomalous X-ray pulsars and soft gamma-ray repeaters which have very long periods and high implied magnetic fields.

3. Pulsar – Supernova Remnant Associations

The youngest pulsar so far discovered in the Parkes multibeam survey is PSR J1119−6127, which has a characteristic age of only 1700 years. An associated supernova remnant might be expected for such a young pulsar, but there was no catalogued remnant at the pulsar position. However, a careful examination of the Molonglo Galactic Plane Survey images (Green et al. 1999) showed a faint ring of emission centered on the pulsar. A deep image at 1.4 GHz made using the Australia Telescope Compact Array (Fig. 2) clearly revealed this emission and showed that it is almost certainly a supernova remnant associated with the pulsar (Crawford et al. 2001).

Several other young pulsars from the Parkes multibeam survey have associated radio nebulae which are probably supernova remnants (Manchester et al. 2002). One of the better examples is PSR J1726−3530 which has a characteristic age of 14 kyr and a surprisingly long period of 1110 ms. As Fig. 3 shows, this pulsar is centrally located within a faint bilateral nebula. Such bilateral struc-

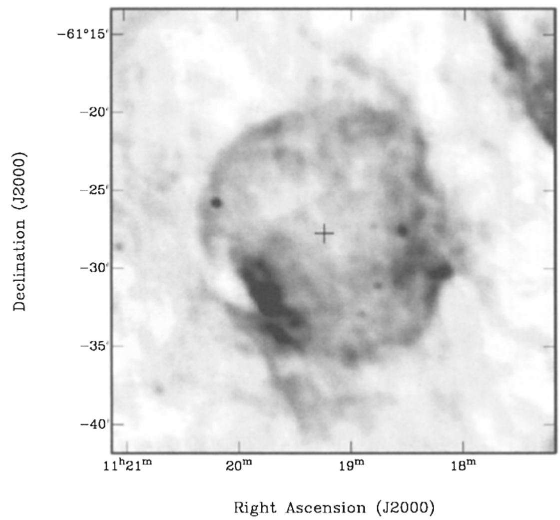

Figure 2. Image of the supernova remnant G292.2−0.5 at 1.4 GHz obtained with the Australia Telescope Compact Array. The position of the young pulsar PSR J1119−6127 is marked with a cross. (Crawford et al. 2001)

tures are relatively common among known supernova remnants (e.g., Gaensler 1998), so it is probable that this faint nebula is a supernova remnant associated with PSR J1726−3530.

Recent searches at both radio and X-ray wavelengths have also revealed several pulsars associated with known supernova remnants. The beautiful *Chandra* image of G292.0+1.8 by Hughes et al. (2001) shows a region of hard emission surrounding a pointlike source about one third of the nebular radius from the center. Hughes et al. suggested that the hard emission is a pulsar wind nebula and that the point source is the pulsar responsible for powering it. However, they were unable to detect pulsations from this source. This region was covered by the Parkes multibeam survey, but there was no known pulsar in this direction. In a determined effort to find the pulsar, Camilo et al. (2002a) made a 10-hour observation in the direction of the supernova remnant using the center beam of the multibeam receiver. Analysis of these data revealed a weak 135 ms pulsar, PSR J1124−5916, with a rapid spin-down rate giving a characteristic age of 2900 years. Any doubt that this was the pulsar associated with G292.0+1.8 was subsequently removed by the detection of pulsations in the X-ray point source at the radio period (J.P. Hughes et al. 2002, private communication). Despite its youth, this pulsar has a radio luminosity of ~ 2 mJy kpc^2, less than that of most known radio pulsars.

In a very similar story, Lu et al. (2002) detected a point X-ray source surrounded by a ring-like nebula in a *Chandra* image of the supernova remnant G54.1+0.3. This combination, strikingly similar to that in the Crab Nebula,

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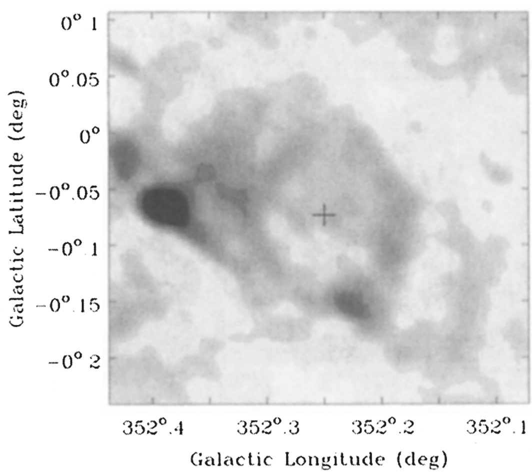

Figure 3. Image of the supernova remnant G352.2−0.1 from the 843 MHz Molonglo Galactic Plane Survey (Green et al. 1999). The cross marks the position of the young pulsar PSR 1726−3530. (Manchester et al. 2002)

strongly suggested the presence of a central pulsar, but again no pulsations could be detected in the X-ray data. Using the Arecibo radio telescope, Camilo et al. (2002b) detected a faint radio pulsar, PSR J1930+1852, in the direction of the supernova remnant. Remarkably, this pulsar has parameters almost identical to those of PSR J1124−5916: pulse period of 136 ms, characteristic age of 2900 years and radio luminosity $\sim$ 1 mJy kpc^2. Its identification with the X-ray point source was confirmed by the detection of pulsations at the same period in archival *ASCA* data.

Despite many years of searching at radio wavelengths, a pulsar had never been detected in the well-known Crab-like supernova remnant, 3C 58, which may be the remnant of a supernova observed in A.D. 1181. A breakthrough came with the detection of pulsations in a central point X-ray source seen in *Chandra* data (Murray et al. 2002). The pulse period is 65 ms and comparison with *RXTE* data from three years earlier gave a period derivative of 1.93×10^{-13} corresponding to a characteristic age of 5370 years. This is not inconsistent with the system being born in A.D. 1181 – it simply implies that the pulsar was born with a period $\sim$ 60 ms. With a knowledge of the pulse period, Camilo et al. (2002c) undertook a very deep radio search using the 100m Green Bank Telescope and detected pulsations at both 1375 MHz and 820 MHz. Fig. 4 shows the X-ray and radio pulse profiles. At X-ray wavelengths, there is a significant interpulse (the Crab pulsar also has a strong interpulse), whereas at radio wavelengths, there is only one pulse per period. It is not yet known if the radio pulse aligns with one or other of the X-ray pulse components.

Other recent discoveries include the detection of 424-ms pulsations from the point source in the large supernova remnant G296.5+10.0 using *Chandra* data

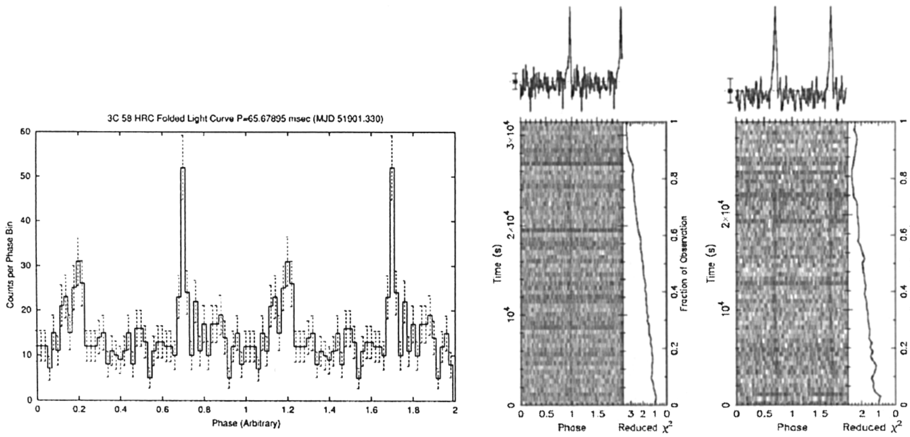

Figure 4. Pulse profiles for PSR J0205+6449 in the supernova remnant 3C 58. The left panel is the *Chandra* X-ray pulse profile (Murray et al. 2002) and the right panels show radio profiles at 1375 and 820 MHz recorded with the Green Bank Telescope (Camilo et al. 2002c)

by Zavlin et al. (2000) and the seredipitious discovery by Gotthelf et al. (2000) of a young pulsar in Kes 75 using *RXTE* observations primarily directed at a nearby anomalous X-ray pulsar. Neither of these pulsars has been detected at radio wavelengths so far. Subsequent *Chandra* observations of PSR J1210-5226 in G296.5+10.0 by Pavlov et al. (2002) showed that it has a characteristic age of order 500 kyr, far greater than any reasonable age for the supernova remnant, and therefore implying that the pulsar was born with a period not much less than its present value. PSR J1846−0258 is located near the center of Kes 75 and, with a characteristic age of only 723 years, is the youngest pulsar known.

Fig. 5 shows the cumulative histogram by year of discovery of clear or at least likely pulsar – supernova-remnant associations. Only two associations (Vela and Crab) were known for more than a decade after the discovery of pulsars. Then there was a more-or-less steady increase over the next 18 years or so, mainly due to radio pulsar searches in the direction of known supernova remnants. The advent of the *Chandra* X-ray telescope with its high spatial and time resolution, together with the very deep radio searches toward known supernova remnants, has dramatically increased the number of believable associations over the past few years so that the total is now 27 plus or minus one or two.

4. Pulsars in Globular Clusters

Globular clusters have proven to be a fertile ground for millisecond pulsar searches. A total of 58 pulsars are now known to be associated with globular clusters, and all but a handful of these have periods of less than 25 ms. Of these, 20 are in the relatively nearby southern cluster 47 Tucanae. All of the 47 Tuc pulsars lie within 2 arcmin of the cluster center, all have pulse periods of between 2 and 8 ms and at least 11 of them are members of binary systems. All

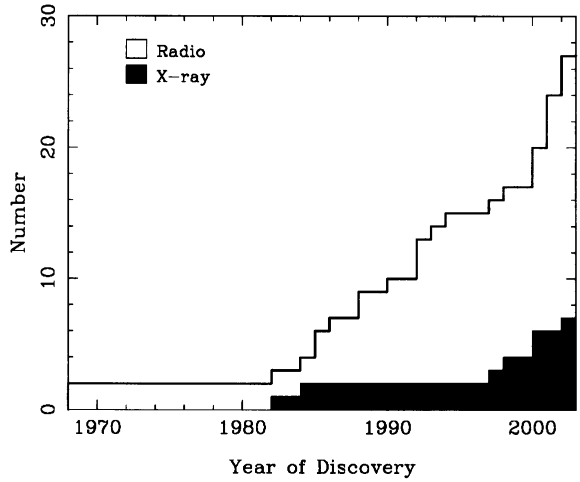

Figure 5. Cumulative histogram of the number of believable pulsar – supernova remnant associations by year of establishment. Associations are separated into two classes, those established by radio observations and those established by X-ray observations. In some cases, discovery of the pulsar establishes the association, whereas in other cases the supernova remnant is discovered by imaging around a known pulsar.

binary companions are very low-mass stars, with probable masses in the range 0.015 to 0.20 $M_\odot$. Nine of the 47 Tuc pulsars were discovered in the past four years using the center beam of the Parkes multibeam receiver (Camilo et al. 2000b). This system has also been used to discover a total of ten millisecond pulsars in four clusters, none of which had a previously known associated pulsar (D'Amico et al. 2001a, 2001b, 2002). One of these, PSR J1807−2459, has the very short orbital period of 1.7 hours and a companion of mass only ~ 0.01 $M_\odot$.

Freire et al. (2001) discovered an interesting correlation between the observed value of $\dot{P}/P$ and the DM as shown in Fig. 6. The observed $\dot{P}$ is dominated by acceleration in the cluster gravitational field, so pulsars with negative $\dot{P}$ are located on the far side of the cluster and most if not all of those with positive $\dot{P}$ are on the near side. The clear correlation of $\dot{P}/P$ with DM can only be accounted for by ionised gas within the central region of the cluster. Stellar winds from evolving stars in the cluster are expected to create such intra-cluster gas, but all previous attempts to detect it have been unsuccessful or at least inconclusive. The total mass of the detected gas is of order 0.1 $M_\odot$, much less than expected; it is likely that relativistic winds from the pulsars in 47 Tuc are responsible for sweeping out most of the gas.

5. Some Recent Timing and Scintillation Results

Of many recent results from Parkes, two which are especially interesting are described here. The first concerns timing observations of PSR J0437−4715, the nearest and strongest millisecond pulsar known. The strength of this pulsar – its

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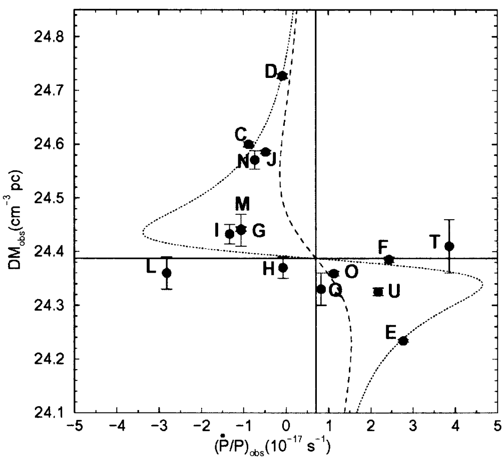

Figure 6. Dispersion measure versus observed $\dot{P}/P$ ratio for pulsars in 47 Tucanae (Freire et al. 2001). The dotted and dashed lines show the expected relation between these quantities for a line of sight passing through the cluster center and 2 pc off the center, respectively.

peak flux density is often several Jy at 1400 MHz – allows measurement of mean pulse profiles with very high signal-to-noise ratio and hence highly accurate pulse timing. Observations made over a two-year interval with a baseband recording system (van Straten et al. 2001) have given an accurate value for the annual parallax of the pulsar, 7.19 ± 0.14 mas, implying a distance of 140 pc, and the first detection of an effect known as annual orbital parallax – the change in the projected pulsar orbit diameter resulting from the annual orbital motion of the Earth. This detection allowed an accurate determination of the pulsar orbit inclination, $42^\circ.75 \pm 0^\circ.09$, and hence a prediction of the size of the Shapiro delay – the delay resulting from the gravitational bending of the ray path as it passes near the binary companion. Fig. 7 shows the predicted and observed timing residuals due to the Shapiro delay. The observations agree well with the prediction, with an rms deviation from the predicted curve of only 35 ns. These results not only provide an independent test of general relativity, but are also the most accurate pulsar timing measurements ever made.

Another nice result obtained using the same baseband observing system is the detection of an orbital variation in the timescale of diffractive interstellar scintillation in the pulsar PSR J1141−6545 by Ord et al. (2002). This pulsar is in an eccentric binary orbit with the short period of 4.75 hours, allowing more than two complete orbits to be observed in one transit of the Parkes telescope. The scintillation timescale varies because of the changing velocity of the pulsar relative to the interstellar diffracting screen as it moves around its orbit. Modelling of this effect gives a measurement of the pulsar space velocity (115 km s^{-1}), the orbit inclination ($76^\circ \pm 2^\circ.5$) and the pulsar and companion masses, 1.29 ± 0.02 M$_\odot$ and 1.01 ± 0.02 M$_\odot$, respectively.

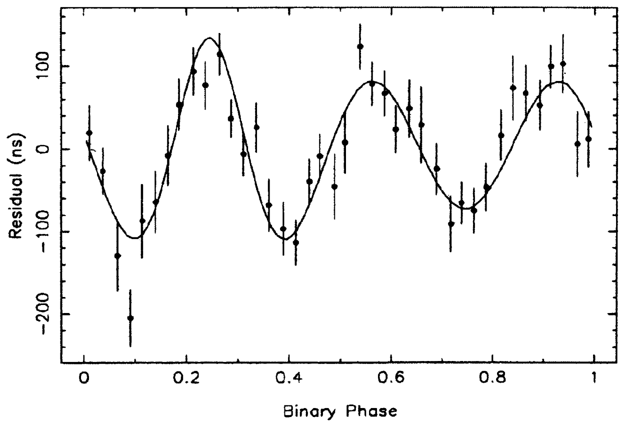

Figure 7. Pulse arrival-time residuals for the binary millisecond pulsar, PSR J0437−4715, showing the predicted and observed signature of the Shapiro delay. Because the inclination angle is not close to 90°, most of the Shapiro delay is absorbed by the first-order Doppler shift, leaving the triple-peaked residual curve. (van Straten et al. 2001)

6. Conclusions

The past few years have seen a wealth of new and interesting results in pulsar research. The large-scale radio pulsar searches have discovered many interesting pulsars and have given a large database for future studies. Multi-wavelength studies, combining radio data with optical, X-ray and γ-ray data are giving new insights, especially in the area of pulsar – supernova remnant interactions. Finally, new receivers and data recording and analysis techniques are giving many new and interesting results. In summary, pulsar research is alive and well, and the future promises to be even better!

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